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EFFECTS OF TARGET LOCATION ON THE SPEED AND ACCURACY OF TAPPING

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Division of
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EFFECTS OF TARGET LOCATION ON THE SPEED AND ACCURACY OF TAPPING

LES EFFETS DE LA LOCALISATION DE LA CIBLE SUR LA VITESSE ET LA PRÉCISION DANS UNE TÂCHE DE FRAPPE

Leslie Buck

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Rapport technique

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ABSTRACT

The experiment reported here was one of a series concerned with the role of target location in motor control theory. It dealt specifically with the question of whether the effects of target location (measured in terms of boundary distance) in a pursuit tracking task were to be found also in tasks of other kinds, and it examined the effects of boundary distance, movement amplitude and target width on the speed and accuracy of performance in a tapping task. The results showed that movement time and movement accuracy varied with boundary distance in the tapping task, although there was a difference in the exact form of the relationship compared to that found in the pursuit tracking task. The main result does however point to the generality of the conclusion that motor performance depends on target location, and thus gives support to theories of motor control which implicate target location as a dominant factor.

RÉSUMÉ

Cette expérience fait partie d'une série d'expériences concernant le rôle que joue la localisation de la cible dans la théorie du contrôle moteur. La question fut de savoir si les effets de la localisation de la cible (mesurée en terme de distance frontière) dans une tâche de poursuite dirigée se retrouveraient aussi dans les autres genres de tâches. On examina donc les paramètres tels que la distance frontière, l'amplitude de mouvement et la largeur de cible en rapport avec la vitesse et la précision de la performance motrice dans une tâche de frappe. L'interprétation des données expérimentales a démontré que dans une tâche de frappe le temps de mouvement et la précision du mouvement variaient selon la distance frontière mais que ce rapport ne prenait pas exactement la même forme dans une tâche de poursuite dirigée. Le résultat principal fait ressortir le caractère général de la conclusion selon laquelle la performance motrice est fonction de la localisation de la cible. Cette expérience vient à l'appui des théories de contrôle moteur qui identifient la localisation de la cible comme un facteur dominant.

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SYMBOLS

Symbol		unit
t	movement time	s
a	movement amplitude	m
w	target width	m

EFFECTS OF TARGET LOCATION ON THE SPEED AND ACCURACY OF TAPPING

1.0 INTRODUCTION

Motor skills constitute an integral part of all aspects of human performance, whether this relates to the control of complex systems and processes or, by contrast, to the manipulation of simple tools, and a full understanding of the interaction between any system or tool and the operator who controls it must necessarily include an understanding of the operator's motor processes. In studying these processes research workers in this area have sometimes directed their attention to seemingly very simple motor activities, and the circumscribed movements under investigation often appear somewhat remote from the rich and varied motor skills manifested in real life. This approach is justified by methodological considerations, and the need to reduce the analytic problem to manageable dimensions, although ironically enough, as new technological developments call upon higher levels of cognitive skill from operators they also call upon simpler control movements. The most complex cognitive decisions are entered into a computer by means of simple key presses, so that control movements are increasingly similar to those found in the motor skill laboratory. Hand movements even so simple as key presses, however, are produced by a complex neuromuscular mechanism, and the objective of motor control theory is to specify the nature and operation of this mechanism, beginning from the preparation of the movement and extending to its final termination.

Inferences about the structure and function of the mechanism underlying motor control are made from measurements of the speed and accuracy of movements carried out under controlled conditions. Changes in the dependent measures of speed and accuracy following from changes in the experimental conditions are ascribed to hypothetical intervening constructs, and at the simplest level this consists of formulating mathematical equations relating the variables in question. Thus Fitts law, which was developed from the view of the operator as a transmittor of information in the manner conceived by information theory, relates movement time to movement amplitude and movement accuracy by the formula:

$$t_1 = k_1 + k_2 \log_2 (2a/w) \qquad (1)$$

where t is time taken to execute the movement, a is movement amplitude (distance between starting and finishing points), w is movement accuracy measured in terms of the width of the target being aimed at, and k_1 and k_2 are constant [Ref. 1]. This formula is one expression of the well-observed speed-accuracy trade-off effect, that as movements become faster they become less accurate. In this case the formula states that as amplitude increases and target width decreases more time is required to make the movement with the same degree of end-point precision. A considerable amount of empirical evidence supports Fitts' theory [Ref. 2], but more recently further evidence has shown that variations

in amplitude and target width do not wholly account for variations in movement time [Ref. 3], and the experiments reported here were carried out as part of a program to investigate this point.

Previous experiments have shown that in a pursuit-tracking task with constant target width movement time depends not only on movement amplitude, but also on a second factor, called boundary distance, which involves the location of the target in relation to the other targets in the display. In this experimental task subjects were required to align a pointer with a target, and as alignment was achieved the target moved to one of four other positions, all five positions being set in line at equal intervals. With this arrangement, the target position could be specified in terms of its distance from the previous position (movement amplitude), and also its distance from the farthest edge of the display in the direction of travel (boundary distance). Movement time depended on both variables. In particular the time for moving between adjacent positions (with constant movement amplitude) increased as the target position (and with it the previous target position) lay closer to the edge of the display (that is, reduced its boundary distance). This was true also for movements of other constant amplitudes. Put another way, targets located closer to the boundary were approached more slowly.

The broader point at issue here concerns the way in which movements are generated and executed. A common theoretical viewpoint has been to conceive a movement as a throwing of the limb from one position to another. Some theorists [Ref. 4, 5] have thought of this in ballistic terms, implying some loss of control between the launch of the limb and its arrival at the target, while others [Ref. 6, 7] have used cybernetic concepts, implying continuous control of the limb by feedback throughout its trajectory. In either case the limb is pushed through its trajectory by appropriate applications of force from behind, as it were, and from this viewpoint the distance to be travelled, or, for the cybernetic theory, the distance yet to be travelled, is the crucial and perhaps the only variable to be considered. If, by contrast, the limb is conceived as being pulled through its trajectory by forces operative at the final aimed end-point [Ref. 8, 9] distance travelled may be less pertinent compared to other factors associated with the location of the end-point. Boundary distance concerns the location of the end-point, and the finding that this affects performance has implications therefore for motor control theory.

The narrower point at issue concerns whether the results obtained with pursuit tracking tasks can be generalized to other tasks. Fitts law is based for the most part on data collected from tapping tasks in which subjects are required to tap a target plate with a stylus. Both our pursuit-tracking task and Fitts' tapping task are alike in that they are subject-paced (subjects work at their own rate and not at one imposed by the experimenter), but they differ in that our subjects controlled the position of the pointer by rotating a steering wheel rather than by direct manipulation of a stylus, and, perhaps more

importantly, our subjects were required to make corrective movements if they initially failed to make a precise alignment while Fitts' subjects simply continued tapping. However, in terms of testing the hypothesis that movement time varies with boundary distance, the important difference is that Fitts used either a single target which was repeatedly tapped or else two targets which were tapped reciprocally, and in both of these cases boundary distance was held constant. This shortcoming can easily be rectified by increasing the number of target positions so that movement amplitude and boundary distance become independently variable, as in our five-position pursuit-tracking task.

The present experiment therefore addressed the question of whether boundary distance effects on movement time are found in a multi-position tapping task. We retained the predictability inherent in Fitts' original tapping task by having subjects tap in a regular manner to and for across the display. Thus movement amplitude remained a between-task factor as in Fitts' experiments, while boundary distance was (necessarily) a within-task factor. Our predictions were that while in two-position tasks movement time would vary with movement amplitude between tasks, in three- and five-position tasks movement time would vary with movement amplitude between tasks and with boundary distance within tasks.

We used movement accuracy as a second dependent measure. In Fitts' paradigm subjects were instructed to maintain a certain hit-rate, and they were required to repeat the trials if this criterion was not reached, the intention being that subjects should maintain movement accuracy at a constant level and should adjust their movement times in order to achieve it. Thus movement accuracy, or, at least, target width, was regarded as an independent variable. However, as Welford [Ref. 5] pointed out, the dispersion of movement end-points is a measure of effective target width which can replace assigned target width in Fitts' equation. We therefore used end-point dispersion, together with constant error (mean end-point distance from target centre) as two measures of movement accuracy.

In our previous experiments with pursuit tracking we showed that movement accuracy measured in terms of end-point dispersion varied with boundary distance, end-points being more dispersed at targets located further from the boundary, and that this accounted for the long-standing finding that overshoot rate varies with boundary distance (targets located closer to the boundary are overshot less frequently) [Ref. 10, 11, 12]. There was no comparable finding implicating constant error, that is the centres of the end-point cohorts were equidistant from the target centre at all targets [Ref. 3]. The second objective in the present experiment therefore was to examine this finding in relation to tapping. Our prediction was that in the three- and five-position tasks end-point dispersion would vary with boundary distance within tasks, while constant error would remain invariable.

2.0 EXPERIMENTAL DESIGN

The experiment used three multi-position tasks (two-position, three-position and five-position) and three movement amplitudes. All subjects performed all Task x Movement-amplitude factor level combinations. In addition the experiment used three target widths as a between-subject variable in order to examine the generality of the results. Three groups of subjects matched for age, sex and handedness were assigned to the narrow- (5 mm), medium- (10 mm) and wide- (20 mm) target widths.

Every subject performed first on the two-position task, secondly on the three-position task, and thirdly on the five-position task. For the two- and three-position tasks targets were presented at between-target distances (movement amplitudes) of 25 mm, 50 mm, and 100 mm, and for the five-position task at distances of 25 mm and 50 mm. The 100-mm distance was too wide for the apparatus in the last case. The order of presentation of movement amplitudes within each task was randomized across subjects.

Each trial consisted of 97 taps. For the three- and five-position tasks subjects began by tapping the middlemost target and then proceeded right or left (depending on handedness) to adjacent targets in that direction, continuing to and fro across the display [Fig. 2.1]. For the two-position task subjects tapped reciprocally beginning by moving right or left depending on handedness. Three consecutive trials were performed at each Task x Movement-amplitude combination, giving 24 trials for each subject.

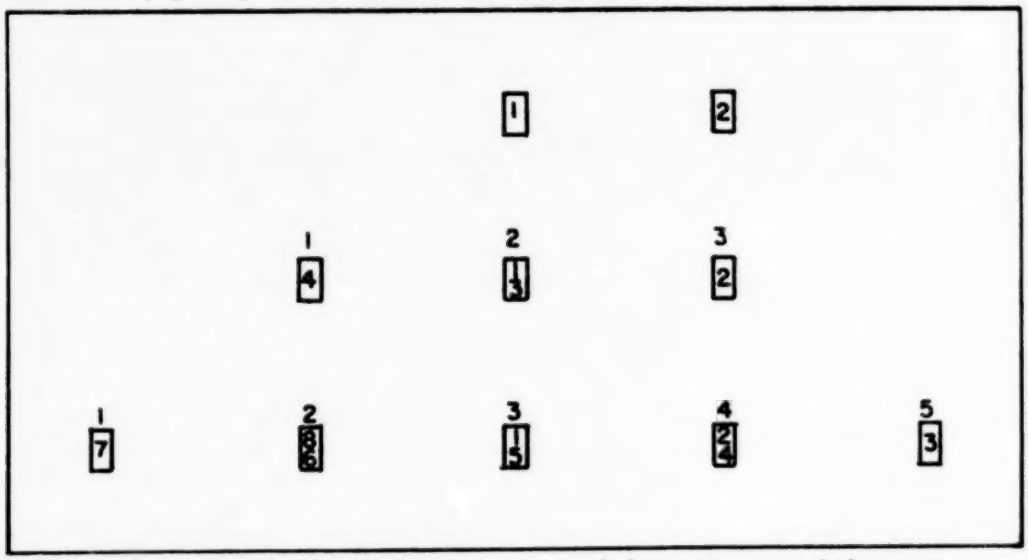

Figure 2.1 Layout of targets for two-position, three-position and five-position tasks

The numbers within the targets denote the order in which they were tapped by right-handed subjects, with each sequence continuing for 97 taps. The numbers above the targets are the position numbers referred to in Table 2.1.

The tapping surface consisted of a translucent perspex plate 42 cm square, mounted on an ultrasonic digitizer. The target was an illuminated rectangle 10 mm high and 5, 10 or 20 mm wide. When it was tapped the target extinguished itself and the next one appeared 25, 50 or 100 mm to the left or right. The stylus emitted a high-pitched tone whose x- and y-coordinates were measured to the nearest 0.25 mm, and this also gave subjects immediate knowledge of having made a successful tap. A PDP 11/60 computer presented the targets and recorded the interval, in milliseconds, between successive taps, and counted the number of taps falling within the illuminated area. If this number fell below 85 the subject was warned and was required to repeat the trial. At the end of each trial subjects were told the total time taken.

Subjects were members of the staff of the National Research Council ranging from 18:8 to 29:10 years in age. Thirty-six were women and 90 were men. Eighteen were left-handed and 108 right-handed.

We took the elapsed time between taps as movement time, following Fitts' procedure. In fact, this elapsed time included a reaction time component, but because movements followed a regular pattern to and fro across the tapping plate, and since subjects knew this to be the case, we assumed that reaction time was short. More importantly, reaction time in a tapping task does not vary with movement amplitude [Ref. 13], and so we assumed that the error produced by our procedure was constant. Movement error was taken as the horizontal distance of the tap from the target centre.

In this data analysis we discarded data from trials which were repeated because of a too-low hit rate. Other data discarded for analysis were those for taps whose coordinates fell outside the illuminated target, those for taps following such cases, and those whose elapsed time exceeded 2000 msec. This latter criterion was based upon inspection of the distribution of all elapsed times. We pooled data across sets of three trials, giving 288 movement times and 288 movement errors in most cases. Data for the three and five-position tasks were categorized by boundary distance as shown in Table 2.1. The numbers of

Task	Movement direction	Boundary-distance level 1	2	3	4
Three-position					
	left	2/1	3/2		
	right	2/3	1/2		
Five-position					
	left	2/1	3/2	4/3	5/4
	right	4/5	3/4	2/3	1/2

Note. Entries are starting/target positions on the tapping surface (see Figure 2.1).

Table 2.1 Categorisation of movements to boundary-distance levels

data in each category were 144 in the three-position task and 72 in the five-position task in most cases, but were sometimes fewer. From each sub-set we calculated a mean movement time, a mean movement error (constant error), and a standard deviation of movement error (end-point dispersion).

3.0 RESULTS

Figure 3.1 shows mean movement times plotted against the value of $\log_2 (2a/w)$ as defined in equation (1). These results show that in general movement time increased with movement amplitude in the manner predicted by Fitts law, although the relationship held less well for the two smaller amplitude levels in the wide-target condition. They show further that movement time decreased with increase in boundary distance, as we predicted. Analyses of variance showed that these effects were all statistically significant [Table 3.1].

Movement amplitude appeared to have no consistent effect on constant error [Table 3.2] even though some of the Amplitude variances were statistically significant [Table 3.1]. Target width affected constant error, but not independently of boundary distance [Table 3.2]. In the two-position task constant error became more negative with increased target width, indicating that targets were undershot to an increasing extent. In the three-position task constant error became more negative with increased target width at boundary-distance level 1, but more positive at boundary-distance level 2, that is in the latter case movements were overshot to an increasing extent. In the five-position task the same interaction was found in that constant error became more negative with increased target width at boundary-distance levels 1 and 2 and more positive at levels 3 and 4. Put the other way round, constant error changed from negative to positive values with increased boundary distance, that is targets located closer to the boundary were undershot and those further from the boundary were overshot, and the magnitude of this effect of boundary distance increased as target width increased. This interactive effect was statistically significant, as shown by the relatively low Width variances (especially in the five-position task) and the high Boundary x Width interaction variance [Table 3.1].

Movement amplitude had a more consistent effect on end-point dispersion than it did on constant error, with end-point dispersion increasing with increased amplitude [Table 3.3]. End-point dispersion also increased with target width, and to a much greater degree than did constant error. The effect of boundary distance, by contrast, was relatively slight. Although Boundary variances were statistically significant, the changes in end-point dispersion were small in magnitude, especially compared to the corresponding changes in constant error, and not consistent with respect to the change in boundary distance.

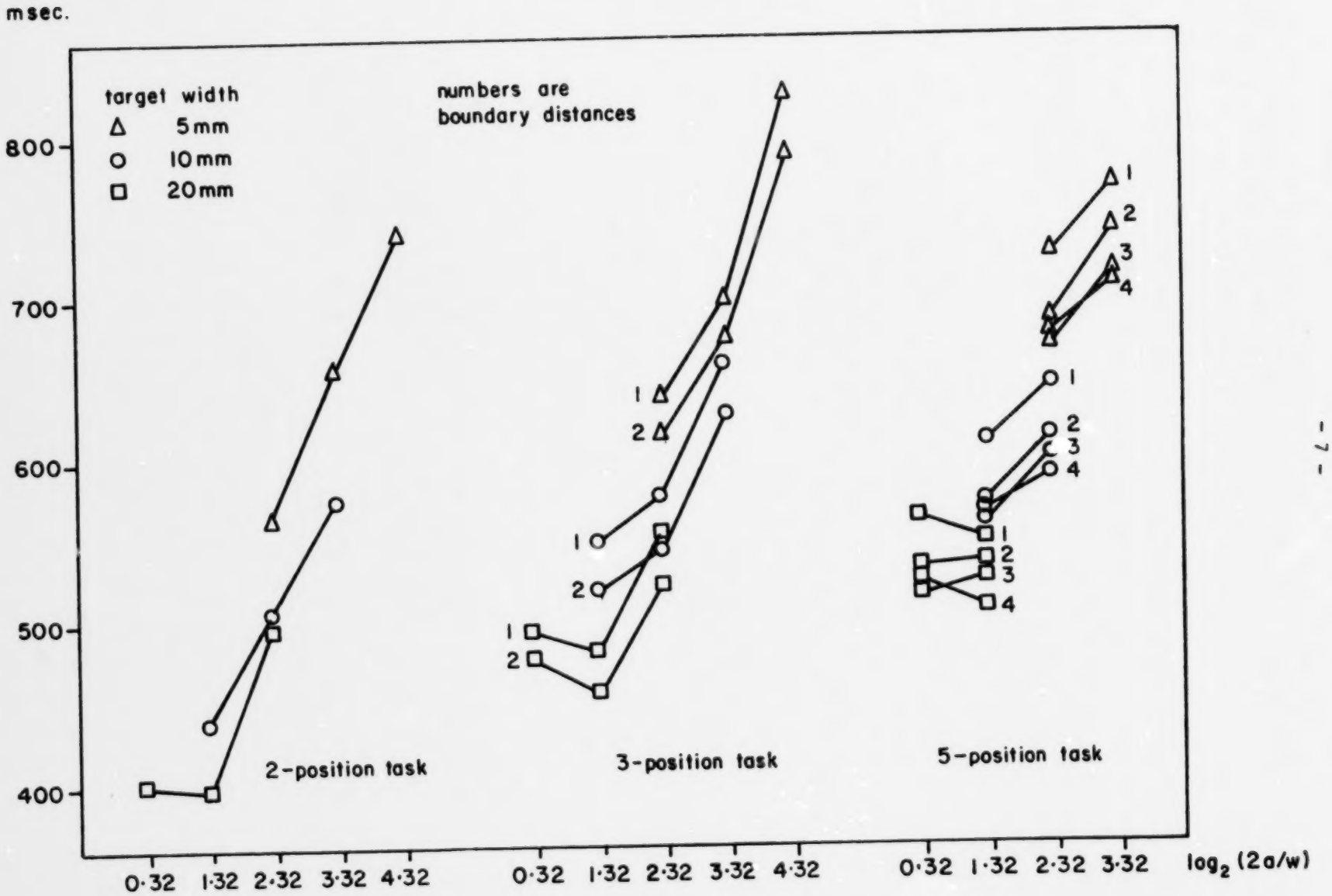

Figure 3.1 Movement Time Plotted Against Index of Difficulty
($Log_2(2a/w)$)

Table 3.1 Summary of analyses of variance

Source		Task: two-position	Task: three-position	Task: five-position
Width	df	2,123	2,123	2,123
	mt	41.60	46.84	45.84
	ce	39.55	19.62	0.32*
	ed	184.30	257.29	279.90
Amplitude	df	2,246	2,615	1,861
	mt	143.21	403.62	176.84
	ce	7.60	7.01	0.34*
	ed	66.32	68.25	61.40
Amplitude x Width	df	4,246	4,615	2,861
	mt	7.68	37.74	56.62
	ce	4.87	0.29*	0.60*
	ed	22.13	28.68	22.51
Boundary	df	-	1,615	3,861
	mt		66.72	112.70
	ce		943.74	588.38
	ed		24.26	6.16
Boundary x Width	df	-	2,615	6,861
	mt		0.43*	1.56*
	ce		34.58	140.44
	ed		8.56	4.52
Boundary x Amplitude	df	-	2,615	3,861
	mt		0.29*	4.82
	ce		12.16	18.74
	ed		4.72	0.39*

Note. All entries except degrees of freedom are F ratios
df - degrees of freedom
mt - movement time
ce - constant error
ed - end-point dispersion
*$p > 0.05$
$p < 0.05$ in all other cases

Table 3.2 Constant error

Boundary distance	Movement amplitude (mm)	Target width (mm) 5	10	20	mean
Two-position task					
1	25	-0.09	-0.33	-1.52	
	50	0.04	-0.25	-0.79	
	100	-0.15	-0.41	-0.92	-0.49
	mean	-0.07	-0.33	-1.08	-0.49
Three-position task					
1	25	-0.41	-1.03	-2.17	
	50	-0.09	-0.54	-1.93	
	100	-0.48	-0.73	-1.87	-1.03
2	25	0.10	0.48	0.92	
	50	0.07	0.26	0.91	
	100	0	0.17	0.36	0.36
	mean	-0.13	-0.23	-0.63	-0.33
Five-position task					
1	25	-0.29	-0.78	-2.51	
	50	-0.52	-1.04	-2.53	-1.28
2	25	-0.21	-0.23	-0.65	
	50	0.02	-0.04	0.02	-0.18
3	25	0.17	0.53	1.46	
	50	0.18	0.65	1.80	0.80
4	25	0.41	0.83	1.84	
	50	0.21	0.54	1.01	0.81
	mean	0	0.06	0.06	0.04

Note. Entries are in millimetres.

Table 3.3 End-point dispersion

Boundary distance	Movement amplitude (mm)	Target width (mm) 5	10	20	mean
Two-position task					
1	25	0.87	1.35	2.03	
	50	0.91	1.53	2.50	
	100	0.91	1.65	2.81	1.62
	mean	0.90	1.51	2.45	1.62
Three-position task					
1	25	0.82	1.40	2.49	
	50	0.89	1.47	2.88	
	100	0.85	1.49	2.97	1.69
2	25	0.81	1.33	2.35	
	50	0.84	1.42	2.56	
	100	0.85	1.49	2.91	1.62
	mean	0.84	1.43	2.69	1.65
Five-position task					
1	25	0.79	1.38	2.49	
	50	0.79	1.41	2.73	1.60
2	25	0.79	1.36	2.71	
	50	0.82	1.46	2.94	1.68
3	25	0.76	1.33	2.65	
	50	0.79	1.40	2.91	1.64
4	25	0.74	1.33	2.57	
	50	0.77	1.43	2.84	1.61
	mean	0.78	1.39	2.73	1.63

Note. Entries are in millimetres.

4.0 DISCUSSION

Subjects performed a two-position tapping task and produced results comparable to those obtained by Fitts and other investigators. The relationship between movement time, movement amplitude and target width found with the two-position task was also evident in the three- and five-position tasks. We may conclude that our experimental task was comparable to Fitts' original task and that the three- and five-position extensions were valid representations of the same task.

The results confirm our prediction that movement time varies with target location measured in terms of boundary distance. Movement time decreased as targets were located further from the boundary, movement amplitude being held constant. The results also confirm that movement accuracy varies with target location, but not in the precise manner predicted. Constant error became more positive as targets were located further from the boundary, but there was no systematic variation in end-point dispersion.

The failure to confirm the second prediction exactly as specified may be accounted for in two ways. First, we may note that our technique for detecting end-point location in the present experiment was superior to that used in our previous experiment [Ref. 3] where our final computations were based on inferences from partially-constructed distributions. This earlier technique took observations relating to the tail of the distribution and from them computed the mean and standard deviation of the total distribution, on the assumption that the total distribution was gaussian in form, and while this was valid in principle it is clearly inferior to a technique based upon direct observation of the total distribution, as in the present experiment. In short, it may be that our earlier conclusion, that boundary distance affected end-point dispersion and not constant error, was erroneous.

The other possibility, and one which respects the integrity of the previous finding, is that the different results were attributable to differences in the characteristics of the tasks and in the strategies adopted by the subjects. Three such differences may be noted. First, subjects were required to tap the targets in a fully predictable sequence to and fro across the display. This was done because we did not have the means of measuring reaction time and, as discussed earlier, we assumed that this pattern of performance resulted in reaction times which were small in magnitude and, more importantly, constant in value. An earlier experiment [Ref. 10] showed that pursuit tracking following a similarly predictable pattern produced an effect of boundary distance upon overshoot rate, but in that experiment no constant error or end-point dispersion data were available. However, in the pursuit tracking experiment reporting an effect of boundary distance on end-point dispersion [Ref. 3], subjects tracked random patterns between target positions, and it is conceivable that this factor (random versus predictable patterns) determined which dependent measure was affected.

A second point of difference is that the two tasks differed in the way in which movements were terminated and end-points created. Taps are, by definition, movements terminated by the imposition of a barrier while the movement itself is in flight, and the barrier creates the end-point. In pursuit tracking, by contrast, the subject terminates the movement by a decelerative action of some kind, so that the subject creates the end-point. While it may not be immediately clear why this should affect the distribution of the end-points, it is possible that this factor determined which dependent measure was affected.

A third point of difference concerns the feedback available to subjects. In our pursuit tracking task subjects had immediate feedback of the accuracy of their movements in that the target was extinguished and a new one presented when precise alignment was achieved, and, furthermore, a failure to achieve immediate alignment led to a disruption in the flow of the movements. This was not true of the tapping task. The target was extinguished when the tapping surface was hit but this happened no matter where the stylus landed, whether within or outside the target, so that it merely indicated that a tap had been made and not how precisely it had hit the target. Indeed, the taps could be made without reference to the targets, and, in fact, occasionally subjects lost contact with the signal presentation, making a sequence of movements which was out of phase with movement of the target. Thus, whereas in pursuit tracking this provided a means for subjects to control their level of overshooting (and could therefore account for the remarkable constancy in overshoot rate with variations in target width), no such mechanism was available in tapping. Whatever means subjects used, therefore, for controlling their accuracy of movement in the tapping task, it was presumably different from that used in the pursuit tracking task, and this may have accounted for which dependent measure was affected by boundary distance.

Given that tapping and pursuit movements differ in these respects, this does not alter the relation between movement time and boundary distance. Boundary distance affects movement time whether this pertains to the partially-truncated movement of a tap made without feedback of movement accuracy, or the more complete movement of pursuit tracking made with accuracy feedback. The locus of the effect must reside therefore in the initial portion of the movement and not in its concluding portion, which in the case of a tap is never actually executed. We may thus infer that when the subject initiates the movement the intent regarding its termination in relation to the boundary of the task has already been formed.

We may conclude that our previous finding that motor performance varies with boundary distance is true for tapping tasks as for pursuit tracking tasks, although the precise nature of the relation as it affects movement accuracy differs in the two tasks. This extension of our finding adds weight to the contention that performance depends on target location (measured here in terms of boundary distance), and thus gives additional support to theories of motor control which emphasizes target location as a critical factor.

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